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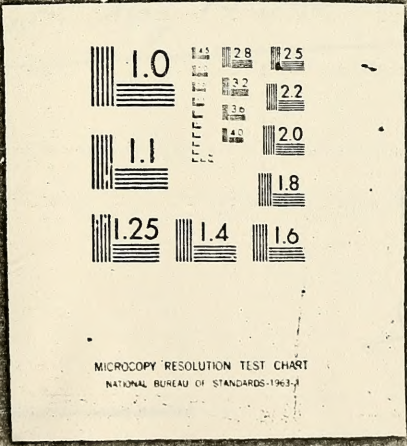

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OTEC ANCHORS: SELECTION AND PLAN FOR DEVELOPMENT.

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by P. J. Valent ~~and~~ J. M. Atturio

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INTRODUCTION

The Civil Engineering Laboratory (CEL) began its work on OTEC anchor systems in May 1975. The Phase I effort was directed toward identifying those anchor types best-suited for mooring OTEC. First, a state-of-the-art review was conducted, collecting all available information necessary to analytically scale the existing anchor types up to the sizes required to moor OTEC [1]. Second, the existing anchor types were scaled up to provide the required holding capacities in five possible seafloor materials. Those anchor types proving unfeasible or impractical were omitted from further consideration. The configurations of the remaining anchor types were optimized to provide a high ratio of lateral holding capacity to weight [2]. Recommendations of anchor types for OTEC are presented in Reference 3. In September 1976, the Phase IIa anchor effort was initiated to: (a) evaluate fabrication, transport, lowering, and seafloor construction techniques and their impact on the proposed anchor designs; (b) select those anchor designs offering an optimal balance between technical feasibility and cost; and (c) prepare a plan for development, outlining the shortcomings in present analytical techniques and construction/installation equipment capability and recommending a course of action necessary to overcome these problems. Phase IIa is now complete and is reported herein.

ANCHOR CONCEPTS DEVELOPED

Site and Loading Conditions

The assumed site and anchor loading conditions are based on two quite different environments: (1) a benign, deep ocean environment and (2) a demanding, Gulf Stream environment. Also, the loading conditions are based on two different sets of plant size and mooring configuration with (1) one set applied during study Phase I, for the selection of anchor types, and (2) a second, less-all-inclusive set applied during study Phase IIa, for the selection of anchor installation techniques. An explanation of the differences in the assumed loading conditions follows.

Phase I. In the deep ocean environment, water depths range from 2,000 to 6,000 m (6,000 to 20,000 ft). The seafloor material is calcareous ooze or pelagic clay. Wind and current load on the power plant was estimated to be about 9 MN (2×10^6 lb) [4,5]. For the Phase I effort, a safety factor of two was applied, yielding an ultimate horizontal component of mooring line load at the anchor of 18 MN (4×10^6 lb). The mooring line angle with the horizontal was assumed to range from 0 to 1.4 rad (80 deg), depending on the mooring system design (Figure 1). Raising the mooring line angle from the horizontal introduces a vertical load component at the anchor. At a mooring line angle of 1.4 rad, this vertical load component amounts to 100 MN (23×10^6 lb).

In the Gulf Stream environment, water depths expected are about 500 to 1,000 m (1,500 to 3,000 ft). The likely seafloor material is sand, gravel, or rock. Loads on the power plants in the Gulf Stream environment are approximately 10 times those in the deep ocean environment [4,5], resulting in an assumed ultimate horizontal component of mooring line load at the anchor, with a safety factor of two, of 180 MN (40×10^6 lb). For this environment, the mooring line angle with the horizontal was assumed to range from 0 to a maximum of 0.8 rad (45 deg), depending on the mooring system design (Figure 2). The vertical load component corresponding to a line angle of 0.8 rad is 180 MN (40×10^6 lb).

Phase IIa. When the Phase IIa was initiated in September 1976, 1 year after Phase I, information generated in other areas of the OTEC program suggested that the OTEC platforms would likely be scaled down in size, thus reducing the horizontal component of load assumed acting on the anchor. Further, CEL engineers had concluded that the use of high mooring line angles – i.e., greater than 0.8 rad (45 deg) – would be undesirable not only because of the greater vertical load capacities required of the anchors, but also because of the much greater mooring line loads accompanying the higher line angles. For these reasons, the loading conditions were modified (reduced in magnitude) to the following:

(1) for the deep ocean environment, the maximum horizontal loading was reduced to 9 MN (2 x 10^6 lb), and the maximum vertical loading was reduced to 9 MN (2 x 10^6 lb)

(2) for the Gulf Stream environment, the maximum horizontal loading was reduced to 90 MN (20 x 10^6 lb), and the maximum vertical loading was reduced to 90 MN (20 x 10^6 lb).

Selection of Anchor Types for OTEC

Anchor Types Considered. The anchor types were placed in four groups to facilitate evaluation (Figure 3): (1) plate anchors (steel plates which are driven edgewise, vertically, deep into the seafloor and then rotated into a horizontal position); (2) drag embedment anchors, such as the STATO, Paravane, or Bruce; (3) pile anchors; and (4) deadweight anchors.

Elimination of Unsuitable Anchors.

(1) Plate anchors. Plate anchors were eliminated early in the anchor selection process because they are simply not suited to developing the mooring line capacities required for OTEC in deep water. Development of the driving system (gun, vibratory hammer, etc.) to drive the plates would be a major effort. Further, this effort would be expended

on an anchoring technique which is not particularly efficient for very large sized plates; e.g., 3 m on a side, because of the embedment distance given up during keying of the fluke [2,3].

(2) Drag embedment anchors. Drag embedment anchors were eliminated as a contender because these anchors require a near horizontal mooring line at the seafloor during embedment or "setting". This near-horizontal mooring line can be achieved only by supplying sufficient deadweight ahead of the anchor, in the form of heavy chain or sinkers, to balance the vertical load component in the mooring line to the platform. It is this configuration that is most commonly used to moor drilling platforms (ship, semisubmersible), but drilling platforms are operating in much shallower water depths than those of the proposed OTEC plants. As will be shown in the "Anchor Lowering" section, lowering of the required deadweight (chain, sinkers, etc.), weighing perhaps 9 to 18 MN (2×10^6 to 4×10^6 lb) is a difficult task, requiring special heavy lift equipment.

There are additional reasons for eliminating the drag embedment anchor from further consideration. First, the drag embedment anchor would be a poor performer in the case of a single-point moor because it is not omnidirectional: The drag embedment anchor will pull out if the direction of load is changed markedly as will typically occur in the deep ocean environment.* Second, industry is not capable presently of manufacturing single anchors large enough to develop the required holding capacity for a mooring leg (assuming 1 to 12 legs). Thus, a group of anchors, in tandem or in series, would have to be used at each anchoring point with all the attendant problems of load handling and positioning in deep water. It is the first reason given, however, (i.e., the large deadweight needed to balance the vertical component of load) that is most significant in removing the drag embedment anchor from further consideration for OTEC use.

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*One anchor type — the Bruce — is advertised as maintaining its embedment with load direction change, but this claim remains to be verified for full-scale anchors.

Relative Merits of Pile and Deadweight Anchors. By process of elimination, then, pile and deadweight type anchors remain as more suitable for use for OTEC. The relative merits of pile versus deadweight anchors, as applied to mooring OTEC, have been presented thoroughly elsewhere [2,3,6]. What follows are brief summaries of the relative merits of these anchors in each ocean environment being studied.

In the typical deep ocean soil profile, piles offer a low lateral load versus material weight efficiency, the efficiency being only slightly better than that of deadweight anchors. The installed cost of the pile system would be higher than that of the deadweight. Further, installation of the pile group anchor is more complicated and requires a longer weather window. For these reasons, the deadweight anchor was selected as the better anchor type for use in the deep ocean.

When the pile and deadweight anchor types are sized to resist the loadings of the Gulf Stream environment, the efficiency balance is noted to shift quite markedly toward pile-type anchors when on rock seafloors. The seafloors beneath the Gulf Stream, where the Stream is close to land, frequently are rock. These high-strength, near-surface materials can be utilized to resist the high horizontal load component. Thus, the pile section design can be changed considerably, thereby significantly increasing the efficiency of the pile-type anchor over that of the deadweight. A modified pile anchor design for use in hard seafloors will be presented later in this report.

Anchor Lowering

The above discussion considers only in-place, service performance of the pile and deadweight anchor types. These anchors, or components of them, must be transported to an OTEC anchor site and then lowered through the water column and safely emplaced on/in the seafloor. Assuming a mooring line angle of 0.8 rad (45 deg) at the anchor, the deadweight anchor for the deep ocean environment will weigh about 31 MN

(7×10^6 lb) in air and about 18 MN (4×10^6 lb) in water. Two basic installation techniques were considered: (1) controlled lowering in one piece or in five elements or (2) free-fall emplacement.

Figure 4 graphically presents the state of the art in the handling of heavy loads in the deep ocean. Two cases were considered for controlled lowering. First, the deep ocean deadweight anchor was assumed to be broken into five components, each weighing 3.6 MN (0.8×10^6 lb) submerged. Second, the deadweight was assumed lowered as one unit weighing 18 MN (4×10^6 lb) submerged.

The drillship falls far short of the required lift capability. Even if the drillship were equipped with 100%-effective motion compensation, it would be able to lower the desired anchor components only to maximum depths of 2,000 m (6,000 ft). Of course such a motion compensation system is far from reality.

The derrick barge, when coupled with a "pipe link" line, such as that proposed for mooring the Lockheed OTEC platform [4], at first glance appears to have significantly greater load-handling capacity than the drillship. However, the crane barge load capacity plotted in Figure 4 also assumes 100%-effective motion compensation, as with the drillship load capacities. Further, the effect of sea and swell on the crane barge capacities are much more pronounced than that on the drillship capacities. In addition to its load capacity limitations, the crane barge technique for lowering the anchor is very limited in the lowering rate that can be achieved. The time required to make and break the joints of the pipe link chain is considerably longer than that required to make and break drill pipe joints: using the pipe link chain, lowering a five element anchor to 6,000 m (20,000 ft) will take in excess of 6 days. To make economical use of the derrick barge with its pipe link chain, the anchor would probably have to be lowered as a unit, limiting the maximum handling depth to about 2,000 m (6,000 ft).

The comparison of state-of-the-art heavy-load handling systems shows that the Glomar Explorer is the only vessel capable of lowering the 18 MN OTEC anchor to water depths of 2,000 to 6,000 m (6,000 to

20,000 ft). That vessel has demonstrated the capability to apply a lifting force estimated at 36 MN (8×10^6 lb) in 5,100 m (17,000 ft) water depth. However, the Glomar Explorer is one of a kind, is quite costly to mobilize, maintain, and operate, and may not be available when needed for OTEC anchor emplacements.

The idea of dividing the anchor into components or building blocks as a means of reducing the payload weights was referred to above when discussing the possibility of anchor emplacement by drillship. The idea of adding buoyancy to the anchor during lowering was also investigated as a possible means of facilitating anchor emplacement by drillship. Light petroleum products (e.g., aviation gasoline), syntactic foams, and air-filled pressure hulls were all considered as possible sources of buoyancy. Buoyancy did serve to reduce the net static load on the lift system; however, the added mass of the buoyancy also acted to increase the dynamic forces arising from vessel motion. This evaluation of buoyancy assist in anchor handling showed that the probability of developing a snap-load condition when lowering the complete 18 MN anchor by drillship, assuming no motion compensation, was quite high. It was also determined that buoyancy-assist in handling 3.6 MN (0.8×10^6 lb) anchor components by drillship (again assuming no motion compensation) would make technically feasible the controlled lowering of those components to water depths of 6,000 m (20,000 ft). A buoyancy system using air-filled pressure hulls, reusable for lowering several OTEC anchors, is the best buoyancy assist approach. However, this system requires five trips to the seafloor to complete the anchor installation. In addition, a sophisticated seafloor positioning control system would be required in order to assemble the anchor components on the seafloor.

In summary, techniques and systems for controlled lowering and emplacement of the 18 MN OTEC anchor are technically feasible, but will prove complicated and expensive.

Initially, free-fall emplacement of 18 MN anchors, though considered, was not highly regarded because of apprehensions regarding stability during free-fall and structural integrity on landing. The

free-fall concept does have certain inherent advantages: it is simple, requires no special equipment, and requires very little ship time on station for installation. Conceptual development of the free-fall concept has built confidence in the advantages of the free-fall concept and has largely dispelled apprehensions regarding stability and structural integrity.

Anchor Systems Developed

Free-Fall-Emplaced Deadweight. The free-fall-emplaced deadweight anchor (Figure 5) is a direct descendant of the high lateral load capacity deadweight anchor designed for controlled lowering [2,3,6]. The grid pattern shear keys of the controlled lowering design has been changed to a radial pattern to provide easy egress for the trapped water beneath the anchor during landing on the seafloor. Also, the periphery of the anchor has been fitted with a device to control vortex shedding to minimize pitching motion during free-fall. Otherwise, the free-fall configuration is the same as the controlled lowering configuration (except for being circular instead of square). The free-fall anchor has been designed for a mooring line load with components of 9 MN (2×10^6 lb) horizontal and 9 MN (2×10^6 lb) vertical – line angle of 0.8 rad (45 deg) with the horizontal – (Phase IIa loading). The free-fall anchor for the Phase IIa loading conditions weighs 18 MN (4×10^6 lb) in seawater and is 33 m (110 ft) in diameter. Air weight for the anchor would be about 31 MN (7×10^6 lb).

The free-fall anchors will be constructed in the dry in a shipyard atmosphere. The construction material will very likely be reinforced concrete with some prestressing in critical areas. The anchors will be transported to the OTEC sites either on barges, or by making the anchors themselves temporarily buoyant and towing them. Loading of a 31 MN (7×10^6-lb) payload on a barge and transporting the payload are demonstrated offshore oil-platform installation capabilities.

Offloading of a nonbuoyant payload weighing 18 MN (4×10^6 lb) in seawater has not been done before, but the feat does not appear overly difficult. Alternatively, the anchor itself can be made to resemble a

barge by adding temporary buoyancy topside to safely float the anchor during its long tow to the OTEC site. Once at the site, the buoyancy compartments would be flooded to initiate the free-fall descent.

The mooring line can be installed either by carrying it to the seafloor on the anchor during emplacement or by lowering and attaching the line to the anchor after emplacement. If the mooring line is carried to the seafloor on the anchor, then the upper end would be released from the anchor after seafloor contact and will be returned to the surface by a syntactic foam-filled float. If the seafloor end of the mooring line is attached after anchor emplant, the line lowering, positioning, and attachment operation would probably be carried out by an appropriately equipped drillship.

Tests with a 0.15-m (6-in.) diameter, scaled model of the free-fall anchor showed that the anchor is stable during free-fall: the anchor will quickly right itself to a horizontal attitude; it does not translate nor rotate during free-fall; and pitching motions are not of serious magnitude - about ± 0.1 rad (± 6 deg). Terminal velocity of the prototype is predicted to be 6 m/s (20 fps) or less.

The structural integrity of the proposed free-fall anchor on landing has not been verified, because the force history and pressure distribution on the anchor during loading are not known. Development of this force and pressure data will require a better understanding of the interaction between the anchor, the water, and the soil on landing for all possible anchor - seafloor orientations. Then structural analysis and design of the anchor can proceed. Time and funding limitations have precluded such an analysis. However, an approximate analysis did show that structural integrity of the free-fall deadweight, when landing on typical deep ocean soil seafloors, will probably not be critical. Even if this preliminary finding should prove faulty, structural integrity during landing can be maintained by decreasing the free-fall velocity of the anchor system. The velocity can be decreased by decreasing the submerged weight of the anchor during free-fall by temporarily adding buoyancy or by increasing the drag on the anchor system by adding drogue buoys.

The free-fall-emplaced deadweight anchor system is also usable on soil seafloors in the Gulf Stream environment, provided that the seafloor is sufficiently compliant to ensure landing and complete embedment of the shear keys without the occurrence of structural distress in the anchor. Rather than using one very large anchor to resist the 180-MN (40×10^6-lb) ultimate lateral load, multiple free-fall deadweight anchors, weighing about 20 MN (5×10^6 lb) submerged each, would probably be used. Individual mooring lines would connect the plant to each anchor with load among lines equalized by an automatic system on the plant.

Pile Group. The seafloors at some potential OTEC power plant sites, notably some of those in the Gulf Stream adjacent to the U. S. coast, will be locally uneven and noncompliant or hard (rock-like). A deadweight anchor is not efficient in developing lateral load capacity on such hard seafloors. Further, a free-fall-emplaced deadweight anchor will very likely suffer serious structural damage if landed on an unyielding, rock-like seafloor. In these local areas of near-surface or exposed hard material, an anchor incorporating piles will often provide the desired anchor holding capacity with far less material weight and probably at lower cost (neglecting technology development costs).

The vertical component of mooring line load and overturning forces on the pile cap/framework would be resisted by tension piles 0.4 to 0.8 m (15 to 30 in.) in diameter by 40 m (130 ft) in length (Figure 6). The horizontal load component would be resisted by short, large diameter stub piles acting much like shear pins between the pile cap and the rock mass. Quite likely, the upper ends of the tension piles will be reamed out to serve as the "shear piles," as shown in Figure 6.

Installation of the pile group anchor would be carried out by first lowering a 4-MN (1×10^6 lb) submerged framework to the seafloor. Lowering of this framework in 500- to 1,000-m (1,500 to 3,000-ft) water depths would be handled by a crane barge or possibly by a drillship (Figure 4). The framework would initially serve as a guide during pile installation. After the pile shells had been grouted into the guides, the framework would serve to distribute the mooring force from the

mooring line attachment point to the individual piles. Drilling of holes for the piles would be done from a drillship using conventional drillhole re-entry techniques for maneuvering the drill-string into the framework drill guides. "Walking" of the drill bit on the rock surface would be prevented by the drill guides. Required drill bit feed thrust would be reduced to manageable magnitudes by developing a hydraulic-powered, rotary impact tool for drilling of holes up to 0.8 m (30 in.) in diameter. Pneumatic tools are now available for drilling such holes in shallow water depths [7]. Hydraulically powered, rotary impact tools, suitable for drilling holes up to 100 mm (4 in.) diameter in water depths of 1,000 m (3,000 ft), have been developed [8]. Thus, when needed, the required 0.8-m-(30-in.) diameter rotary impact drill can be developed. Sufficient thrust for conventional reaming of the upper drillhole to diameters of 2 m (6 ft) can be developed by hanging a drill collar-like assembly from the reamer bit and allowing the reamer bit to support this mass in the tension pile drillhole.

After each drillhole is completed, a steel tension member and integral shear collar would be grouted into the drillhole and template drill guide using conventional techniques. The drillship would later attach the mooring line to the anchor framework attachment point.

Procedures for analysis of pile group anchors on hard (rock) seafloors are satisfactory; however, those procedures for design and installation would definitely require improvement and development before a pile anchor design is selected for an OTEC plant.

Such improvement and development of the pile anchor system is not warranted at this time because its use by OTEC plants is foreseen to be very limited and because, when used, the pile anchor system will be quite expensive and time-consuming to install. Postponing and possibly cancelling development of the pile anchor system does not mean that OTEC exploitation of the thermal difference resource in the Gulf Stream area should also be postponed or abandoned. Rather, siting of the OTEC plants will depend on finding a seafloor environment suitable for using free-fall deadweight anchors; i.e., several meters of unconsolidated sediments overlying rock. Available information indicates that most of

the area beneath the Gulf Stream is of this nature. It may be that other constraints may also direct OTEC plant siting in this direction; for example, if burial of an electric power cable to shore is necessary, then siting on unconsolidated sediment would be a necessity.

Anchor Selection

Reliable, long-lasting anchor systems capable of maintaining the OTEC power plant on station in a single- or multiple-point moor are technically feasible.

The free-fall-emplaced deadweight anchor for use on soil seafloors is very attractive because it does not require any specialized ship support except the ocean-going tugs required to tow it to the proposed anchor location. Because almost all of the proposed OTEC plant locations are in areas having soil seafloors, the free-fall-emplaced deadweight anchor merits high development priority. Procedures for predicting the forces on the free-fall anchor should be assembled and verified by model tests of reliable scale. A near-prototype-scale free-fall anchor should be fabricated, transported, installed, and test-loaded, if possible, to verify all aspects of the free-fall anchor system.

Installation of the free-fall-emplaced anchor may not be feasible on hard seafloors, especially on exposed rock. The lateral holding capacity efficiencies and general performance of deadweight anchors on such seafloors (especially uneven seafloors) are not attractive. If OTEC anchor siting on a hard seafloor area is absolutely necessary, then a specialized pile anchor group installed by drillship could be used. Development work on a pile anchor system should be deferred until a necessary site floored with near surface or exposed rock has been identified. Deferral is prudent at this time (1) because the authors anticipate that most such sites can be avoided with an overall cost savings and (2) because the design of the pile system will be largely site specific with minimal benefit derived from a generalized study.

PLAN FOR DEVELOPMENT – OTEC ANCHORS

As indicated above, the free-fall deadweight anchor embodies areas of new technology. Thus, this anchor type will require: (1) the development of these new technology areas and (2) a near prototype scale demonstration to ensure contractor acceptance of this new technology. The following plan for development will accomplish these goals.

The plan for development addresses only the free-fall deadweight anchor. The pile group anchor, intended for use on very hard seafloors (rock), is not addressed here because the development investment does not appear at this time to be warranted for the OTEC program.

The plan for development is divided into two phases: (1) technology development using analytical techniques and large scale models and (2) an anchor system demonstration including the construction, transport, emplacement, and service loading of a near-prototype-size anchor. These two program phases are depicted in time in Figure 7.

Technology Development Phase

The technology development phase has been divided into the following three elements:

(1) Hydrodynamic evaluation of the free-fall anchor

(2) Description of the soil penetration-deceleration forces history for the anchor

(3) Development of anchor structural design to withstand construction, transport, free-fall, landing, and service loadings.

The elements cannot be interchanged as information generated in (1) is required to initiate (2) and so on.

Hydrodynamic Evaluation. The hydrodynamic evaluation can be separated into two parts: behavior during constant velocity fall and during deceleration upon approaching the seafloor.

Evaluation of the behavior during free-fall would seek to minimize all instabilities of the anchor during free-fall, including even slight pitching motions, if possible. This evaluation is best carried out by testing models of sufficient size so as to have a drag coefficient equal to that of the prototype. Preliminary information indicates that a model 1 m in diameter, giving a scaling ratio of 1:30, will provide that equality. The drag coefficient for the anchor in free-fall is known to be a constant for Reynolds numbers between 10^3 and 10^6 (1-m-diameter model), and it is expected to remain constant for Reynolds numbers up to 10^8 (30-m-diameter prototype). Data for Reynolds numbers for 10^6 to 10^8 are not available and cannot be obtained in the laboratory; thus, a test of the large scale anchor is the only true test of the validity of this engineering judgment. After achieving a stable free-fall shape, this model would require further evaluation to determine the effects of realistic induced perturbations on stability.

Then, evaluation of the behavior during seafloor approach is necessary to determine the water pressure distribution on the underside of the anchor, the velocities of the water escaping from beneath the landing anchor, and the anchor deceleration due to the trapped water (or water-cushion effect). An analytic approach followed by verifying model tests appears appropriate to obtain this deceleration information for the case of a stably falling, horizontal anchor approaching a horizontal seafloor. Following this simple case, the more normal case of a sloped seafloor and a perturbed anchor must be addressed. Preliminary information indicates that the water-cushion effect will work to orient the anchor parallel to the seafloor while slowing its descent rate. Reliable analysis techniques are needed here to predict the orientation of the anchor during its descent and especially at the point of contact with the seafloor. The exiting water velocity, water pressure distribution, and the anchor velocity, orientation, and angular momentum data are all required input to the following soil penetration/deceleration analysis and in turn to the anchor structural design to resist possible loadings during landing.

Soil Penetration-Deceleration Force History. After some degree of deceleration due to the water-cushion effect, the anchor shear keys will touch the seafloor and begin to displace soil as they penetrate. The soil penetration generates an increasing resisting force as the shear keys penetrate down to stronger soils, and as greater volumes of soil are accelerated into motion to make way for the penetrating structure. Then the anchor base itself comes into contact with the soil causing still another change in the deceleration mode as the much greater area of the base begins to penetrate the seafloor.

This soil-penetration/anchor-deceleration interval must be analytically described and modeled to obtain the load distribution on the anchor during penetration. These data along with the inertial force distribution are necessary to structurally analyze and design the anchor. Development of an analytical model treating the ideal case of horizontal anchor and horizontal seafloor appears an appropriate first step. Physical modeling would follow to improve the analytical model. Then this analytical model would be altered to include the case of the perturbed anchor and the sloping seafloor.

Structural Analysis and Design. Once the anchor, soil, and water forces are known and understood, then the development of structural analysis and design techniques for the anchor can proceed. Structural design concepts will make optimum use of materials and fabrication labor while maintaining the stable hydrodynamic design. Also in this element, the adequacy of the structural design to resist forces during transport, offloading from a barge, and its service life will be determined.

At the conclusion of this final element of the technology development phase, the tools will be in hand for the analysis and design of prototype OTEC anchor systems. These tools will have been validated by tests with reliably scaled models (preliminary information indicates dimensional scaling of 1:30 is appropriate). Validation of the analytic technique and demonstration of the concept by a full-sized, prototype anchor will be the next step in ERDA development of the OTEC anchor system.

Demonstration Anchor

Transfer of the free-fall-emplaced, deadweight anchor technology to industry will require a demonstration of the anchor concept using a near-prototype-scale anchor. This demonstration anchor system would probably be designed for and utilized as a mooring for the planned 5 MWe OTEC Pilot Power Plant. The following text elaborates on this demonstration phase.

Design Anchor. A suitable test-site/construction-site combination would be selected. All available data on the proposed anchor test site would be collected and evaluated to develop a preliminary profile of soil engineering properties with depth and a preliminary picture of areal variation. A set of anchor requirements would be selected to fit the test requirements, and a preliminary design prepared using the analytical model developed. Concurrently, a site survey would be made, if necessary, to enhance the geotechnical data bank and to provide additional quantitative input for the demonstration anchor final design. The preliminary anchor design would then be reviewed in light of the necessary specific site data and a final working design prepared.

Fabricate Anchor, U-joint, Mooring Line, and Instrumentation.* When a final design has been reached for the demonstration anchor, then fabrication of mooring components by selected contractors can begin. Fabrication of the anchor would probably be accomplished in a shipyard.

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*Because this report is directed toward anchors for OTEC, other parts of the total mooring have not been mentioned, although these parts — e.g., mooring line, buoyancy elements, U-joint — have all had an impact on the final anchor recommendations. The mooring line would probably be braided synthetic with syntactic foam buoyant elements attached along the lower part of the line to make that lower part positively buoyant. The U-joint, located between the mooring line and the anchor, would draw on those designs that have been service-proven in single-point moorings for tanker loading/unloading.

The instruments required to monitor anchor performance would require careful conceptual and preliminary design before fabrication is initiated. The U-joint and mooring line would be contracted to experienced manufacturers.

Transport and Install Anchor. After the anchor is fit with its instrumentation and, possibly, the U-joint and mooring line installed, the anchor would either be floated out using attached buoyancy tanks or it would be loaded onto a launching barge for sea transport. If transported in a self-floating mode the anchor would be supported by several integral or attached air-filled buoyancy tanks. All facets of the anchor installation and mooring line deployment would be carried out to complete the demonstration. The attached instrumentation should monitor the anchor behavior during free-fall descent and during landing on the seafloor. Arrangements should be made for visual inspection of anchor attitude and condition shortly after the landing.

Test Anchor. Full testing of the mooring system will require two efforts: (1) a long-term serviceability test of the mooring system, and (2) a short-term proof loading of critical mooring system components.

The purpose of the long-term serviceability test is to demonstrate the durability of the mooring system components (especially the mooring line, U-joints, and swivels) in a near-prototype-size installation and to verify the station-keeping performance of the mooring system in response to those wind, current, and wave forces that do occur during the 1-yr minimum test period. This mooring system test is expected to be a part of the 5-MWe OTEC pilot power plant installation. In the event such a combined mooring and 5-MWe platform test is not advisable due to other OTEC program constraints, then the mooring system could be tested under the load of some other suitable surface platform acting as a dummy load.

Unfortunately, this long-term load test – with the 5-MWe pilot plant or a dummy surface platform – will not verify the ultimate load capacity and probably will not demonstrate whether the mooring system can resist the design load, because the design storm required to supply

the loading will probably not occur during the test period. Controlled loading of the mooring system in deep water, at an acceptable site for a serviceability test, would require a number of ocean-going tugs, would be very difficult to achieve, and would be economically unjustified. Instead, the design load capacity of the mooring system should be demonstrated by:

1. Proof loading of mooring line specimens and U-joints and swivels in a terrestrial test facility before and after deployment in the serviceability test

2. Very limited model anchor testing, using the 1-m-diameter model from the hydrodynamic tests, to verify the assumed soil deformation patterns under various combinations of lateral and vertical load in both clays and sands

It is possible, of course, to determine the ultimate lateral holding capacity of the anchor by placing the anchor in a nearshore location where the required lateral load could be supplied by winches tied to deadmen, with both established on terra firma. The anchor could be both lowered to the shallow seafloor (e.g., 10 to 20 m) and recovered, using attached tanks of compressed air for varying the buoyancy. Such a test of ultimate load capacity is at this time considered not cost effective.

Recommend Practice. Following demonstration of this free-fall anchor technology to industry, this technology should be documented, difficulties noted, and possible solutions indicated. This guide for practice should include details on optimum shear key configuration, thoughts on when to consider scour protection and approaches to correcting potential scour problems, and thoughts on in-place ballasting of the deadweight anchor to increase its load capacity. Possibly this recommended practice guide could offer several "standard" free-fall anchor designs. The standard anchor designs would be established to accommodate a particular near-surface seafloor soil condition and a particular loading condition. Standardized anchor designs should reduce overall costs by eliminating the cost of repeated, individual design for each anchor and by providing for standardization or reuse of some fabrication and forming items.

Summary

The plan for development of OTEC anchors (illustrated in Figure 7) is arranged to complete installation of the demonstration, free-fall-emplaced, deadweight anchor by April 1980. The demonstration anchor is thus scheduled to be available to serve in the mooring system for the proposed 5-MWe OTEC pilot power plant. This plan goes far beyond the anchor itself – to the fabrication and testing of a complete mooring leg, because it is the total mooring leg that makes a meaningful, useful package.

Certain points demand special reference. First, the proposed schedule is very tight. To meet the mooring installation date of April 1980, technology development for the free-fall anchor must be initiated in early October 1977. Second, the plan, specifically the cost figures, assumes a single-point moor. Fouling of the mooring line on the cold water pipe during slack loading periods is assumed to be minimized by equipping the plant with an under-rated dynamic positioning system to keep the plant outside a minimum radius watch circle. The cost estimate does not include the cost of the under-rated dynamic positioning system. Third, the plan assumes that mooring line loads are sufficiently low that they can be safely resisted by near off-the-shelf designs for line, line terminations, U-joints, and swivels – i.e., design loads are less than 3 MN (0.7×10^6 lb) – safety factor of 3 assumed on 0.25-m (10 in.) diameter braided synthetic. If higher loads are to be applied, then costs and probably the time duration of the mooring plan will increase to accommodate required line development and hardware engineering.

The plan for development calls for installation of the mooring during March 1980, to be completed to receive the 5-MWe pilot plant in April. Close monitoring of performance of this mooring system will continue for about 12 months, after which a periodic inspection schedule would be set up. Results of this anchor/mooring demonstration will be evaluated with adequate time remaining for design, fabrication, transport, and installation of a prototype anchor to serve in the mooring for the planned 25-MWe OTEC in early 1983.

CONCLUSIONS AND RECOMMENDATIONS

The free-fall emplaced, deadweight anchor is the best anchor type for use with OTEC at all potential OTEC power plant sites except possibly for those few with exposed hard rock seafloors. Technology development for the free-fall-emplaced anchor should be initiated during October 1977 to ensure installation of the demonstration anchor by April 1980. The recommended start-date is also necessary to ensure subsequent fabrication, transport, and installation of a prototype anchor in January 1983 to serve in the mooring system for the proposed 25 MWe OTEC demonstration power plant.

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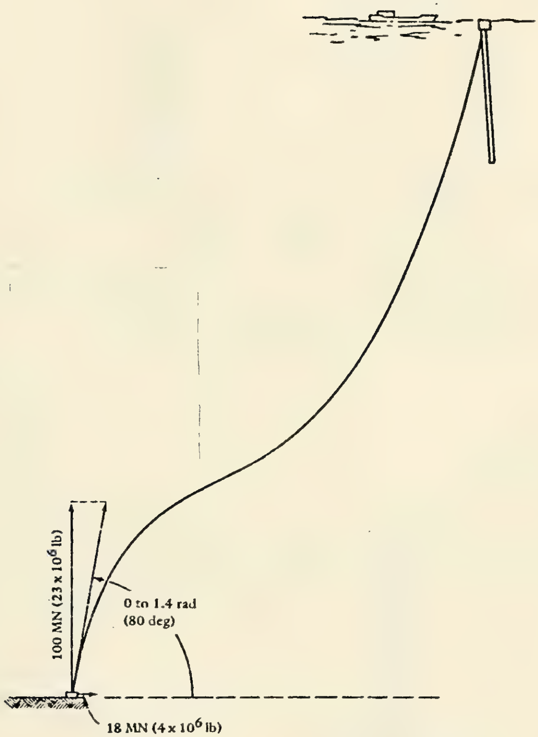


Figure 1. Anchor loadings, deep ocean environment, Phase I.

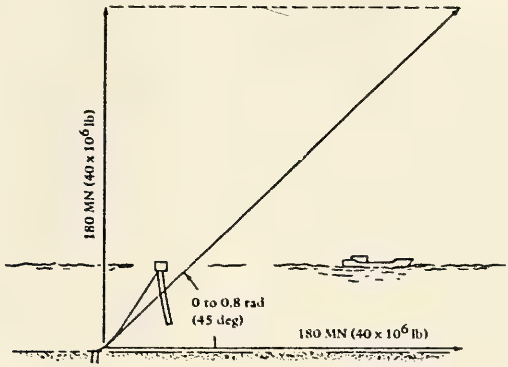


Figure 2. Anchor loadings, Gulf Stream environment, Phase I.

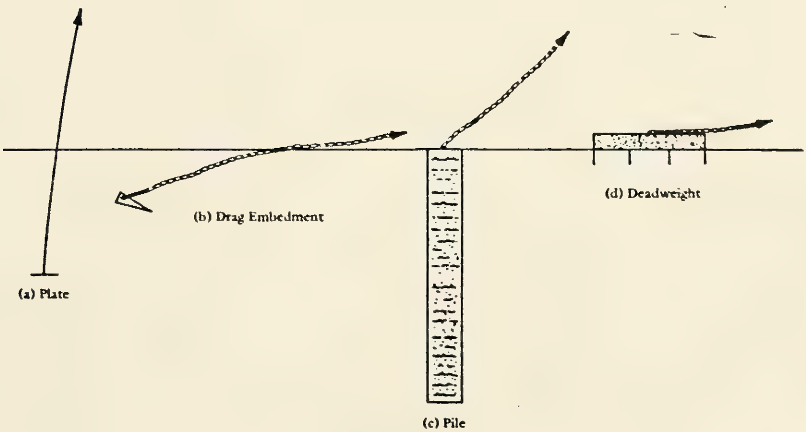


Figure 3. Anchor groups considered.

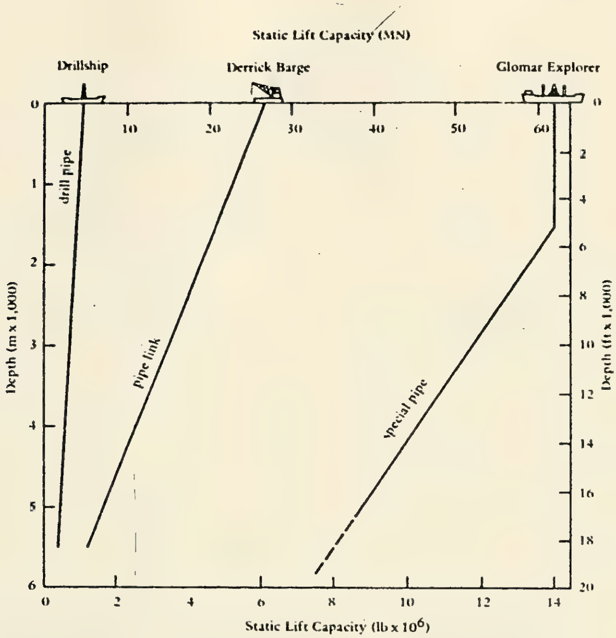


Figure 4. State of the art in heavy-lift vessels.

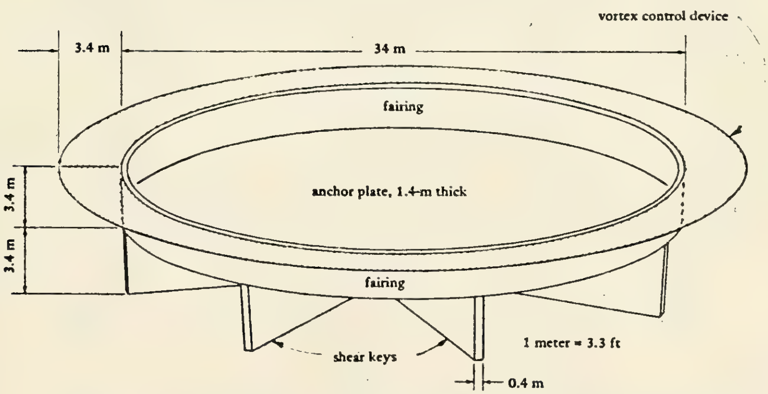


Figure 5. Oblique view of free-fall-emplaced deadweight anchor.

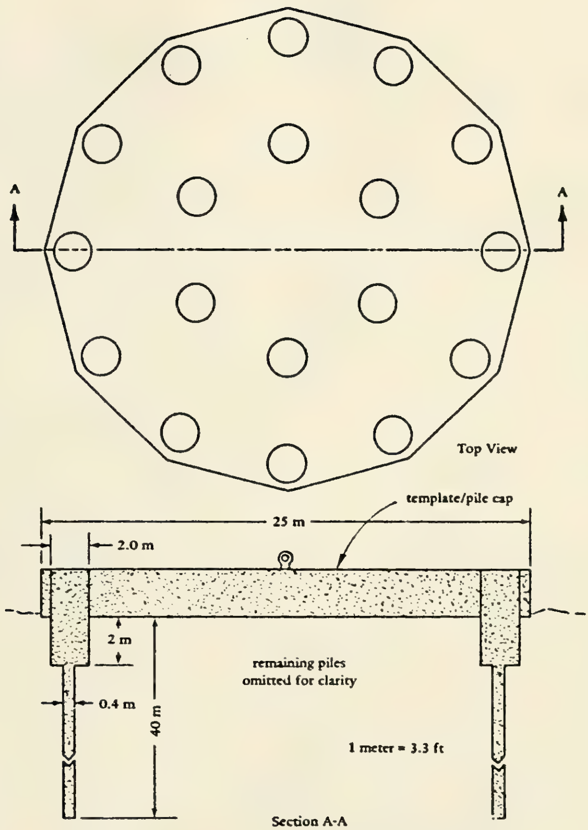
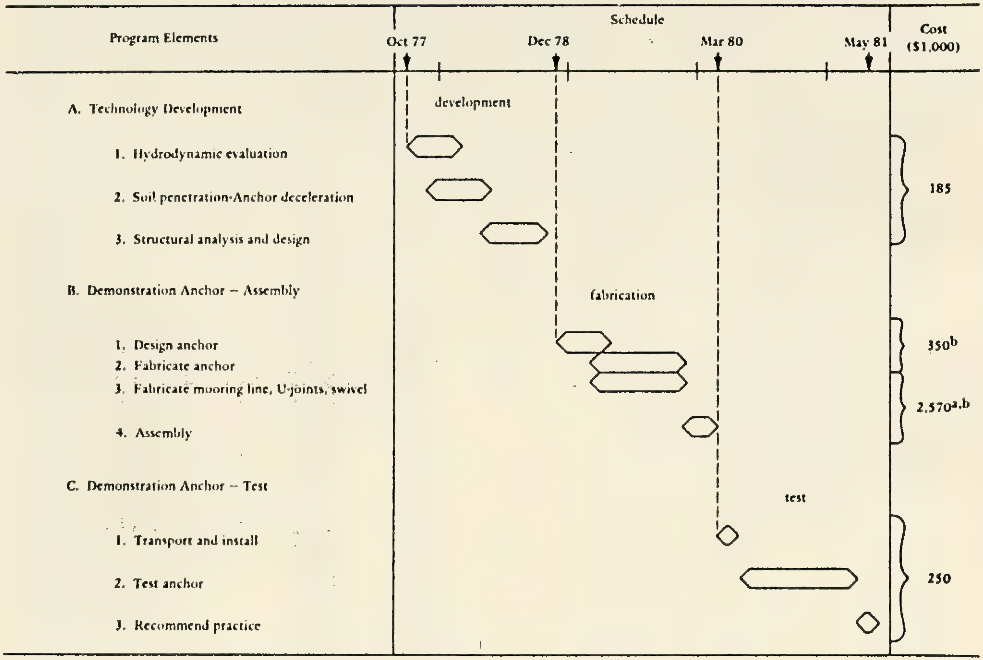


Figure 6. Anchor pile group for Gulf Stream environment.



[a] Costs do not include possible engineering for the synthetic line.
[b] Costs are for one mooring leg only and do not include cost of under-rated dynamic positioning system required with a single-point moor with OTEC.

Figure 7. Plan for development of OTEC anchors.

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